

Is Our Universe Natural?¹

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It goes without saying that we are stuck with the universe we have. Nevertheless, we would like to go beyond simply describing our observed universe, and try to understand why it is that way rather than some other way. Physicists and cosmologists have been exploring increasingly ambitious ideas that attempt to explain why certain features of our universe aren't as surprising as they might first appear.

What makes a situation “natural”? Ever since Newton, we have divided the description of physical systems into two parts: the configuration of the system, characterizing the particular state it is in at some specific time, and the dynamical laws governing its evolution. For either part of this description, we have an intuitive notion that certain possibilities are more robust than others. For configurations, the concept of entropy quantifies how likely a situation is. If we find a collection of gas molecules in a high-entropy state distributed uniformly in a box, we are not surprised, whereas if we find the molecules huddled in a low-entropy configuration in one corner of the box we imagine there must be some explanation.

For dynamical laws, the concept of naturalness can be harder to quantify. As a rule of thumb, we expect dimensionless parameters in a theory (including ratios of dimensionful parameters such as mass scales) to be of order unity, not too large nor too small. Indeed, in the context of effective quantum field theories, the renormalization group gives us some justification for this notion of “naturalness” [1]. In field theory, the dynamics of the low-energy degrees of freedom fall into universality classes that do not depend on the detailed structure of physics at arbitrarily high energies. If an interaction becomes stronger at large distances, we expect it to be relevant at low energies, while interactions that become weaker are irrelevant; anything else would be deemed unnatural.²

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²The parallel between natural states being high-entropy and natural theories arising from the renormalization group is essentially an analogy, although there has been some tentative work towards establishing a more formal connection – in particular, linking Boltzmann's *H*-theorem describing the evolution of entropy and the *c*-theorem describing renormalization-group flow [2, 3]. See for example [4].

| Scale | Energy | Length |
|--------------------------------|--|---|
| Planck (Gravitation) | $E_{\text{pl}} = (8\pi G)^{-1/2} \sim 10^{27} \text{ eV}$ | $L_{\text{pl}} \sim 10^{-32} \text{ cm}$ |
| Fermi (Weak interactions) | $E_F = (G_F)^{-1/2} \sim 10^{11} \text{ eV}$ | $L_F \sim 10^{-16} \text{ cm}$ |
| QCD (Strong interactions) | $E_{\text{QCD}} = \Lambda_{\text{QCD}} \sim 10^8 \text{ eV}$ | $L_{\text{QCD}} \sim 10^{-13} \text{ cm}$ |
| Vacuum (Cosmological constant) | $E_{\text{vac}} = \rho_{\text{vac}}^{1/4} \sim 10^{-3} \text{ eV}$ | $L_{\text{vac}} \sim 10^{-2} \text{ cm}$ |
| Hubble (Cosmology) | $E_H = H_0 \sim 10^{-33} \text{ eV}$ | $L_H \sim 10^{28} \text{ cm}$ |

Table 1: Orders of magnitude of the characteristic scales of our universe, in units where $\hbar = c = 1$. The reduced Planck energy is derived from Newton’s constant G ; the Fermi scale of the weak interactions is derived from Fermi’s constant G_F . The QCD scale Λ_{QCD} is the energy at which the strong coupling constant becomes large. The vacuum energy scale arises from the energy density in the cosmological constant. The Hubble scale characteristic of cosmology is related to the total density ρ by the Friedmann equation, $H \sim \sqrt{\rho}/E_{\text{pl}}$. Note the large dynamic range spanned by these parameters.

If any system should be natural, it’s the universe. Nevertheless, according to the criteria just described, the universe we observe seems dramatically unnatural. The entropy of the universe isn’t nearly as large as it could be, although it is at least increasing; for some reason, the early universe was in a state of incredibly low entropy. And our fundamental theories of physics involve huge hierarchies between the energy scales³ characteristic of gravitation (the reduced Planck scale, $E_{\text{pl}} = 1/\sqrt{8\pi G} \sim 10^{27}$ electron volts), particle physics (the Fermi scale of the weak interactions, $E_F \sim 10^{11}$ eV, and the scale of quantum chromodynamics, $E_{\text{QCD}} \sim 10^8$ eV), and the recently-discovered vacuum energy ($E_{\text{vac}} \sim 10^{-3}$ eV).⁴ Of course, it may simply be that the universe is what it is, and these are brute facts we have to live with. More optimistically, however, these apparently delicately-tuned features of our universe may be clues that can help guide us to a deeper understanding of the laws of nature.

I will survey some recent ideas for confronting these problems of naturalness, both with respect to the state of the universe and the laws of physics. The choice of ideas to consider is completely ideosyncratic, but should serve to give a flavor for the types of scenarios being considered in the more speculative corners of contemporary cosmology.

The state of our universe.

Consider the state in which we find our observable universe. On very large scales the distribution of matter is approximately homogeneous and isotropic, and distant galaxies are expanding away from each other in accordance with Hubble’s law. Extrapolating into the past, the universe originated in a hot, dense state about fourteen billion years ago. The deviations from perfect smoothness that we observe today have grown via gravitational

³Throughout this paper I will use units in which $\hbar = c = 1$, so that $1 \text{ eV} = 1.8 \times 10^{-33} \text{ g} = 5.1 \times 10^4 \text{ cm}^{-1} = 1.5 \times 10^{15} \text{ sec}^{-1}$.

⁴We will not consider neutrino masses, which have not yet been accurately measured.

instability from initially small perturbations of approximately equal amplitude on all length scales. Interestingly, the “ordinary matter” made of particles described by the Standard Model of particle physics is only about 4% of the total energy of the universe; another 23% is some “dark matter” particle that has not yet been discovered. Even more interestingly, 73% of the universe is “dark energy,” some form of smoothly-distributed and nearly-constant energy density [5, 6, 7]. The most straightforward candidate for dark energy is vacuum energy, or the cosmological constant: an absolutely constant minimum energy of empty space itself, with a density $\rho_{\text{vac}} \sim E_{\text{vac}}^4 = (10^{-3} \text{ eV})^4$ [8].

If the universe were in a “likely” configuration, we would expect it to be in a high-entropy state: *i.e.*, in thermal equilibrium. Unfortunately, we do not have a rigorous definition of entropy for systems coupled to gravity, but we can make simple estimates. The entropy of matter and radiation (neglecting gravity) in our observable universe is approximately the number of massless particles, $S_M(U) \sim 10^{88}$. This was the dominant contribution at early times when the matter distribution was essentially smooth; today, however, inhomogeneities have formed through gravitational collapse, creating large black holes at the centers of galaxies, and these black holes dominate the current entropy [9]. The Bekenstein-Hawking entropy of a black hole is proportional to its horizon area, $S_{BH} = A/4G \sim 10^{77}(M_{BH}/M_\odot)^2$. Since there are probably more than ten billion galaxies in the observable universe with million-solar-mass black holes at their centers, the current entropy in black holes is at least $S_{BH}(U) \sim 10^{99}$. If we were to combine all of the matter in the observable universe into one giant black hole, the entropy would be significantly larger, $S_{\text{max}} \sim 10^{120}$. So our universe is currently in a rather low-entropy configuration, and it started out much lower.⁵

Faced with the question of why our universe started out with such a low entropy, most cosmologists would appeal to inflation [10, 11, 12, 13]. According to this idea, a very tiny patch of space dominated by false vacuum energy undergoes a period of rapidly accelerated expansion, smoothing out any inhomogeneities and ultimately reheating to the radiation-dominated early state of the conventional Big Bang model. For inflation to begin, the initial patch must be quite smooth itself [14]; but because it is so small, one imagines that it can’t be that hard to find an appropriate region somewhere in the chaotic conditions of the early universe.

It is worth emphasizing that the *only* role of inflation is to explain the initial conditions of the observable universe. And at this it does quite a good job; inflation predicts that the universe should be spatially flat, and should have a scale-free spectrum of adiabatic density

⁵The fact that entropy tends to increase is of course just the Second Law of Thermodynamics, and makes sense once we assume that the initial entropy was low. The puzzle is why the early universe should differ so dramatically from the late universe, despite the intrinsic time-reversibility of the microscopic laws of physics; this is known as the “arrow of time” problem.

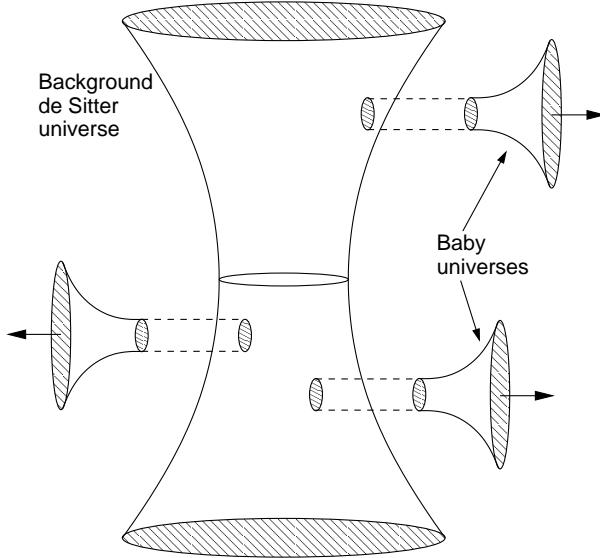


Figure 1: A possible spacetime diagram for the universe on ultra-large scales. A natural state for a universe with a positive vacuum energy is empty de Sitter space. In the presence of an appropriate scalar field, quantum fluctuations in such a background can lead to the nucleation of baby universes. Each baby universe is created in a proto-inflationary state, which then expands and reheats into a universe like that we observe.

perturbations [15, 16, 17, 18], both of which have been verified to respectable precision by observations of the cosmic microwave background [7]. But we are perfectly free to imagine that these features are simply part of the initial conditions – indeed, both spatial flatness and scale-free perturbations were investigated long before inflation. The only reason to invoke inflation is to provide a reason why such an initial condition would be *natural*.

However, as Penrose and others have argued, there is a skeleton in the inflationary closet, at least as far as entropy is concerned [9, 19, 20]. The fact that the initial proto-inflationary patch must be smooth and dominated by dark energy implies that it must have a very low entropy itself; reasonable estimates range from $S_I \sim 10^0 - 10^{20}$. Thus, among randomly-chosen initial conditions, the likelihood of finding an appropriate proto-inflationary region is actually much *less* than simply finding the conditions of the conventional Big Bang model (or, for that matter, of our present universe). It would seem that the conditions required to start inflation are less natural than those of the conventional Big Bang.

One possible escape from this conundrum has been suggested under the name of “spontaneous inflation” [21], a particular implementation of the idea of “eternal inflation” [22, 23, 24, 25] (for related ideas see [26, 27, 28]). In general relativity, high-entropy states correspond to *empty space*; given any configuration of matter, we can always increase the entropy

by expanding the universe and diluting the matter degrees of freedom [21]. But if empty space has a nonzero vacuum energy, it can be unstable to the creation of baby universes [29, 30, 31, 32, 33, 34]. In an empty universe with a positive cosmological constant (de Sitter space), quantum fluctuations will occasionally drive scalar fields to very large values of their potentials, setting up precisely the conditions necessary to begin inflation. The resulting bubble can branch off into a disconnected spacetime, leading to an inflating region that would resemble our observable universe.

Needless to say, scenarios of this type are extremely speculative, and may very well be completely wrong. One mysterious aspect is the process of baby-universe creation, which certainly lies beyond the realm of established physics. In the context of string theory, there seem to be circumstances in which it can happen [35, 36, 37, 38] but also ones in which it cannot [39]; whether it will occur in realistic situations is still unclear. Another issue is the nature of gravitational degrees of freedom in the context of the holographic principle (see *e.g.* [40]). Given the relevance of inflation to observable phenomena, however, it is important to establish that inflation actually solves the problems it purports to address. In spontaneous inflation, there is a simple explanation for the low entropy of the initial state: it's not really “initial,” but rather arises via quantum fluctuations from a pre-existing de Sitter state with very large entropy and a very low entropy density. Whether this particular idea is on the right track or not, it is crucial to understand whether inflation plays a role in explaining how our observed configuration could be truly natural.

The laws of physics.

The dynamical laws of nature at the microscopic level (including general relativity and the Standard Model of particle physics) are tightly constrained in the form that they may take, largely by symmetry principles such as gauge invariance and Lorentz invariance. The specific values of the numerical parameters of these theories are in principle arbitrary, although on naturalness grounds we would expect mass/energy scales to be roughly comparable to each other.

As mentioned in the introduction, however, that is not what we observe: the Planck scale, Fermi scale, QCD scale, and vacuum-energy scale are separated by huge hierarchies. In the case of QCD this is understandable; the characteristic scale is governed by the logarithmic running of the QCD coupling constant, so a hierarchy isn't that surprising. The difference between the Planck and Fermi scales ($E_{\text{pl}}/E_F \sim 10^{16}$) is a celebrated puzzle in high-energy physics, known simply as “the hierarchy problem”; ideas such as supersymmetry may provide partial answers. The discrepancy between the Planck scale and the vacuum-energy scale ($E_{\text{pl}}/E_{\text{vac}} \sim 10^{30}$) is another puzzle, “the cosmological constant problem”; most researchers agree that there are no compelling solutions currently on the market.

In contemplating the nature of these hierarchies, a complicating factor arises: we couldn't exist without them. If all of the energy scales of fundamental physics were approximately equal, it would be impossible to form structures in which quantum gravity didn't play a significant role, and the large cosmological constant would make it difficult to imagine any complex structures at all (since the rapidly-accelerating expansion of the universe would work to tear things apart). One can imagine two very different attitudes in the face of this situation:

1. We just got lucky. The constants of nature just happen to take on values consistent with the existence of complex organisms.
2. Environmental selection. The parameters we observe are not truly fundamental, but merely reflect our local conditions; hospitable regions of the universe will always exhibit large hierarchies.

Within the first case, there are two separate possibilities: either we are *really* lucky, in the sense that the observed hierarchies are truly unnatural and have no deeper explanation, or there exist unknown dynamical mechanisms which make these hierarchies perfectly natural. The latter possibility is obviously more attractive, although it is hard to tell whether such dynamical explanation will eventually be forthcoming.

Environmental selection, sometimes discussed in terms of the “anthropic principle,” has received renewed attention since the discovery of the dark energy. The basic idea is undeniably true: if our observable universe is only a tiny patch of a much larger “multiverse” with a wide variety of local environments, there is a selection effect due to the fact that life can only arise in those regions that are hospitable to the existence of life. Of course, to give this tautology any explanatory relevance, it is necessary to imagine that such a multiverse actually exists.

Existence of the multiverse requires two conditions: the *possibility* of multiple vacuum states with differing values of the constants of nature, and the *realization* of those states in distinct macroscopic regions. Recent ideas in string theory suggest that there may be a “landscape” of metastable vacua arising from different ways of compactifying extra dimensions in the presence of branes and gauge fields – numbers such as 10^{500} vacua have been contemplated, promising more than enough diversity of possible local conditions [41, 42, 43, 44, 45, 46]. Meanwhile, the possibility of eternal inflation discussed in the previous section provides a mechanism for realizing such states: quantum fluctuations can lead to episodes of inflation that reheat into universe-sized domains in any of the permitted vacuum states [47]. Thus, the ingredients of the multiverse scenario seem to be in place, even if they remain quite speculative.

If all the multiverse does is *allow* for the existence of a region that resembles our own, it adds nothing to our understanding; it is equally sensible to say that our universe is simply like that. Instead, the possible epistemological role of the multiverse is to explain why our observed parameters are natural. In principle, the multiverse picture allows us to *predict* the probability distribution for these parameters. In particular, the probability $P(X)$ that an observer measures their universe to have feature X (such as “the ratio of the vacuum energy scale to the Planck scale is of order 10^{-30} ”) will be roughly of the form

$$P(X) = \frac{\sum_n \sigma_n(X) V_n \rho_n}{\sum_n V_n \rho_n}. \quad (1)$$

In this expression, the index n labels all possible vacuum states; $\sigma_n(X)$ equals 1 if vacuum n has property X and 0 if it does not; V_n is the spacetime volume in vacuum n ; and ρ_n is the spacetime density of observers in vacuum n .

Obviously, there is some imprecision in the definition of (1); for example, we have been vague about what constitutes an “observer.” (For attempts at more precise formulations of an equivalent expression, see [48, 49, 50, 51, 52, 53].) This expression suffices for our current purpose, however, which is to point out that actually calculating the probability is at best beyond our current abilities, and at worst completely hopeless. Just to mention the most obvious difficulty: in the context of eternal inflation, there is every reason to believe that the volumes V_n of some (if not all) vacua are infinite, and the expression is simply undefined.

The fact that (1) is undefined hasn’t stopped people from trying to calculate it. The most famous example is Weinberg’s prediction of the magnitude of the cosmological constant [54, 55, 56]. This calculation imagines a flat prior distribution for the vacuum energy, keeping all other parameters fixed, and relies on the fact that the universe recollapses in the presence of a large negative vacuum energy and expands too quickly for galaxies to form in the presence of a large positive vacuum energy. Under these assumptions, the predicted value of ρ_{vac} is not too different from what has been observed; moreover, the prediction was made before the measurement. Attempts have also been made to apply similar reasoning to models of particle physics [57, 58, 59, 60, 61].

Unfortunately, there is little reason to be satisfied with this calculation of the expected vacuum energy. In terms of (1), it is equivalent to imagining that the factor $\sigma_n(X)$ counting appropriate vacua is distributed uniformly in ρ_{vac} , the volume term V_n is simply a constant, and the density of observers ρ_n is proportional to the number of galaxies. The first of these is a guess, the second is likely to be fantastically wrong in the context of eternal inflation, and the last only makes sense if all of the other parameters are held fixed, which is not how we expect the multiverse to work. For example, allowing the amplitude of primordial

density fluctuations to vary along with the vacuum energy can dramatically change the result [62, 63, 64, 65].

At the present time, then, there is *not* a reliable environmental explanation for the observed value of the cosmological constant. Meanwhile, other attempts to use anthropic reasoning lead to predictions that are in wild disagreement with observations [66]. But objections to the credibility of the apparently-successful predictions of the multiverse idea have equal force when applied to the apparently-unsuccessful predictions; whether or not the idea is falsifiable, it would be an exaggeration to say that it's already been falsified.

More importantly, limitations in our current ability to calculate expectation values in the multiverse are not evidence that there isn't some truth to the idea itself. If we eventually decide that environmental selection plays no important role in explaining the observed parameters of nature, it will be because we somehow come to believe that the parameters we measure locally are also characteristic of regions beyond our horizon, not because the very concept of the multiverse is aesthetically unacceptable or somehow a betrayal of the Enlightenment project of understanding nature through reason and evidence.

Discussion.

Naturalness is an ambiguous guide in the quest to better understand our universe. The observation that a situation seems unnatural within a certain theoretical context does not carry anything like the force of an actual contradiction between theory and experiment. And despite our best efforts, naturalness is something that is hard to objectively quantify.

The search for naturalness plays an important role as a *hint* of physical processes that are not yet understood. In particle physics, attempts to find a natural solution to the hierarchy problem have driven investigations into supersymmetry and other models; in cosmology, attempts to explain the uniformity and flatness of our contemporary universe helped drive the development of the inflationary scenario. We can hope that attempts to understand the cosmological constant and the low entropy of the early universe will lead to compelling new ideas about the fundamental architecture of nature.

The scenarios discussed in this paper involve the invocation of multiple inaccessible domains within an ultra-large-scale multiverse. For good reason, the reliance on the properties of unobservable regions and the difficulty in falsifying such ideas makes scientists reluctant to grant them an explanatory role [67]. Of course, the idea that the properties of our observable domain can be uniquely extended beyond the cosmological horizon is an equally untestable assumption. The multiverse is not a theory; it is a *consequence* of certain theories (of quantum gravity and cosmology), and the hope is that these theories eventually prove to be testable in other ways. Every theory makes untestable predictions, but theories should be judged on the basis of the testable ones. The ultimate goal is undoubtedly ambitious: to

construct a theory that has definite consequences for the structure of the multiverse, such that this structure provides an explanation for how the observed features of our local domain can arise naturally, and that the same theory makes predictions that can be directly tested through laboratory experiments and astrophysical observations. Only further investigation will allow us to tell whether such a program represents laudable aspiration or misguided hubris.

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